Sci. Bull. (2016) 61(2):172–177
DOI 10.1007/s11434-015-0982-x

www.scibull.com
www.springer.com/scp

Article

Physics & Astronomy

From strangelets to strange stars: a unified description

Cheng-Jun Xia · Guang-Xiong Peng · En-Guang Zhao · Shan-Gui Zhou

Received: 10 October 2015 / Revised: 12 November 2015 / Accepted: 7 December 2015 / Published online: 16 January 2016

Abstract The conventionally separated treatments for strangelets and strange stars are now unified with a more comprehensive theoretical description for objects ranging from strangelets to strange stars. After constraining the model parameter according to the Witten–Bodmer hypothesis and observational mass–radius probability distribution of pulsars, we investigate the properties of this kind of objects. It is found that the energy per baryon decreases monotonically with increasing baryon number and reaches its minimum at the maximum baryon number, corresponding to the most massive strange star. Due to the quark depletion, an electric potential well is formed on the surface of the quark part. For a rotational bare strange star, a magnetic field with the typical strength in pulsars is generated.

Keywords Strangelets · Strange stars · Strange quark matter · Unified description · Witten–Bodmer hypothesis

C.-J. Xia (✉) · E.-G. Zhao · S.-G. Zhou
State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
e-mail: cjxia@itp.ac.cn

G.-X. Peng
School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China

G.-X. Peng
Theoretical Physics Center for Science Facilities, Institute of High Energy Physics, Beijing 100049, China

G.-X. Peng · S.-G. Zhou
Synergetic Innovation Center for Quantum Effects and Application, Hunan Normal University, Changsha 410081, China

E.-G. Zhao · S.-G. Zhou
Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China

1 Introduction

It was pointed out long ago that strange quark matter (SQM) might be the ground state of strongly interacting matter, which is nowadays called the Witten–Bodmer hypothesis [1, 2]. If true, there should exist stable objects of SQM with the baryon number A ranging from a few to $\sim 10^{57}$. Customarily, small SQM nuggets with $A \lesssim 10^7$ are often referred to as strangelets [3–10], or slets [11], while stars consisting of SQM are called strange (quark) stars [12–21], being possible candidates for pulsars.

Lumps of SQM are expected to be produced in the collision of binary compact stars containing SQM [22, 23]. Further collisions among those lumps may create slets, nuclearites [24, 25], meteor-like compact ultradense objects [26] etc., and some of them may eventually make their way to our Earth [27]. Due to the special characteristics of these objects such as the lower charge-to-mass ratio [28, 29], the larger mass [30], the highly ionizing tracks in the interstellar hydrogen cloud (e.g., pulsar scintillations) [31], and the characteristic gamma rays through heavy ion activation [32], there are possibilities to observe them. However, despite decades of efforts, no compelling evidence for the existence of stable SQM is found (for reviews, see, e.g., Refs. [33, 34]).

This case is due to the extreme complexity of an SQM system which involves all the fundamental interactions, i.e., the strong, weak, electromagnetic, and gravitational interactions. In the conventional theoretical treatments, significantly different simplifications were adopted for slets and strange stars. For a slet, electrons were ignored since the Compton wavelength is much larger than the size of the quark part [35], and quarks were assumed to be uniformly distributed. For strange stars, gravity has to be considered. The normal way is to first get an equation of state of SQM by assuming the local charge neutrality and then obtain the mass–radius (*M*–*R*) relation by solving the Tolman–Oppenheimer–Volkov equations.

However, according to recent studies, effects such as the charge screening, electron–positron pair creation, and non-zero charge densities in strange stars have important implications on the properties of SQM. For example, taking into account the electrostatic effects, Alford et al. [36] found that, for a small enough surface tension, large slets are unstable to fragmentation and strange star surfaces fragment into a crystalline crust made of slets and electrons. For quark–hadron phase transition, the finite-size effect turns out to be very important [37–40]. It was shown that the geometrical structures may be destabilized by the charge screening effect [41]. Due to the electron–positron pair creation, an upper bound on the net charge of slets or strange stars was found [42]. The local charge neutrality in compact stars is also in question [43]. In the case of a neutron star, an overcritical electric field was found in the transitional region from the core to the crust [44]. For a bare strange star, an electric dipole layer may be formed on the surface and result in an electric field of $\sim 10^{17-19}$ V/cm [12]. Due to the presence of a critical electric field, the electron–positron production may be induced and results in some astrophysical observables [45]. The mass and radius of a strange star are increased by $\sim 15\,\%$ and $\sim 5\,\%$, respectively, if the star possesses a net charge on the surface [46].

Meanwhile, the possibility of pulsars being strange stars may give us an insight into the properties of SQM. Up till now, around 2,500 pulsars have been observed, and among them about 70 pulsars' masses were measured (Ref. [47] and http://www.atnf.csiro.au/research/pulsar/psrcat/). At the same time, more than 10 pulsars provide us the *M*–*R* probability distributions with photospheric radius expansion bursts as well as quiescent low-mass X-ray binaries [48–52]. If SQM is absolutely stable, those pulsars may be strange stars [53], and then the properties of SQM can be constrained with the *M*–*R* relations.

In the present paper, we study the SQM system ranging from slets to strange stars in a unified description. After constraining the only model parameter, the bag constant *B*, according to the Witten–Bodmer hypothesis and the observational *M*–*R* probability distribution of pulsars, it is found that the ratio of charge to baryon number of a slet is different from previous findings, while the size is significantly smaller than that of a nucleus with the same mass number. In addition, rotation of a bare strange star generates a strong magnetic field with the typical strength in pulsars.

2 Theoretical framework

The internal structure of a spherically symmetric, charged, and static object should fulfill the thermodynamic equilibrium condition, which can be obtained by minimizing the energy of the system for given total particle number and entropy. We consider the gravity and electrostatic interactions on the macroscopic scale. The metric for the SQM sphere reads

$$\mathrm{d}s^2 = \mathrm{e}^{\nu}\mathrm{d}t^2 - \mathrm{e}^{\lambda}\mathrm{d}r^2 - r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2), \quad (1)$$

where r, θ, and ϕ are the standard spherical coordinates with the metric elements satisfying

$$\mathrm{e}^{-\lambda} = 1 - \frac{2G}{r}M_{\mathrm{t}}, \quad (2)$$

$$\frac{\mathrm{d}\nu}{\mathrm{d}r} = \frac{2G\mathrm{e}^{\lambda}}{r^2}\left[4\pi r^3\left(P - \frac{\alpha Q^2}{8\pi r^4}\right) + M_{\mathrm{t}}\right]. \quad (3)$$

Here we use the natural system of units, with G and α being the gravitational and fine-structure constants. The total mass, particle number, and entropy are obtained with

$$M_{\mathrm{t}}(r) = \int_0^r 4\pi r'^2\left(E + \alpha Q^2/8\pi r'^4\right)\mathrm{d}r', \quad (4)$$

$$N_i(r) = \int_0^r 4\pi n_i(r')\mathrm{e}^{\lambda/2}r'^2\mathrm{d}r', \quad (5)$$

$$\bar{S}(r) = \int_0^r 4\pi S(r')\mathrm{e}^{\lambda/2}r'^2\mathrm{d}r'. \quad (6)$$

Then the total charge is given by $Q(r) = \sum_i q_i N_i(r)$ with $q_u = 2/3$, $q_d = q_s = -1/3$, and $q_e = -1$. Based on the Thomas–Fermi approximation, the pressure $P(r)$, energy density $E(r)$, particle number density $n_i(r)$, and entropy density $S(r)$ are given locally by incorporating both the strong and weak interactions.

By minimizing the mass $M = M_t(\infty)$ with respect to the particle distribution $N_i(r)$ and entropy distribution $\bar{S}(r)$ at the fixed total particle number $N_i(\infty)$ and entropy $\bar{S}(\infty)$, we immediately have

$$\frac{\mathrm{d}\mu_{\mathrm{i}}}{\mathrm{d}r} = \frac{Q}{r^2}q_i\alpha\mathrm{e}^{\lambda/2} - \frac{\mu_i}{2}\frac{\mathrm{d}\nu}{\mathrm{d}r}, \quad (7)$$

$$\frac{\mathrm{dT}}{\mathrm{d}r} = -\frac{T}{2}\frac{\mathrm{d}\nu}{\mathrm{d}r}, \quad (8)$$

with $\mu_i(r)$ and $T(r)$ being the chemical potential and temperature.

For the local properties of SQM, we adopt the bag model and consider only zero temperature, where the thermodynamic potential density is given by